Preprint
UCRL-JC-143853

The Interaction of Supernova Blast Waves with Interstellar Clouds: Experiments on the Omega Laser

R. I. Klein, H. F. Robey, T. S. Perry, J. O. Kane, J. A. Greenough, M. Marinak

This article was submitted to
2nd International Conference on Inertial Fusion Science Applications
Kyoto, Japan
September 9-14, 2001

U.S. Department of Energy

Lawrence
Livermore
National
Laboratory

August 17, 2001

The Interaction of Supernova Blast Waves with Interstellar Clouds: Experiments on the Omega Laser

R. I. Klein[1,2], H. F. Robey[1], T. S. Perry[1], J. O. Kane[1], J. A. Greenough[1], M. Marinak[1]

[1]*University of California*
Lawrence Livermore National Laboratory,
Livermore, California 94550
[2]*Berkeley, Department of Astronomy*

ABSTRACT

The interaction of strong shock waves, such as those generated by the explosion of supernovae with interstellar clouds, is a problem of fundamental importance in understanding the evolution and the dynamics of the interstellar medium (ISM) as it is disrupted by shock waves. The physics of this essential interaction is critical to understanding the evolution of the ISM, the mixing of interstellar clouds with the ISM and the viability of this mechanism for triggered star formation. Here we present the results of a series of new OMEGA laser experiments investigating the evolution of a high density sphere embedded in a low density medium after the interaction of a strong shock wave, thereby emulating the supernova shock-cloud interaction. The interaction is viewed from two orthogonal directions enabling visualization of the both the initial distortion of the sphere into a vortex ring as well as the onset of an azimuthal instability that ultimately results in the three-dimensional breakup of the ring. These studies augment previous studies [1,2] on the NOVA laser by enabling the full three-dimensional topology of the interaction to be understood. We show that the experimental results for the vortex ring are in remarkable agreement with the incompressible theory of Widnall [3]. Implications for mixing in the ISM are discussed.

1. INTRODUCTION

The interaction of shock waves in the interstellar medium (ISM) such as those associated with supernovae, stellar winds, bipolar flows, and HII regions with interstellar clouds, is critical to our understanding the evolution of the ISM, the mixing of interstellar clouds with the ISM, and the viability of this mechanism for triggered star formation as shown by Klein et al. [4-5]. In these studies, several instabilities (Richtmyer-Meshkov, Rayleigh-Taylor, and Kelvin-Helmholz) were shown to play a role in the turbulent breakup and mixing of the cloud. In addition, these studies have pointed out the important role played by non-axisymmetric bending mode instabilities in vortex rings of the type studied by Widnall et al. [3,6] for incompressible flows.

Several previous experimental studies have focussed on this basic fluid dynamic problem. Haas and Sturtevant [7] performed shock tube experiments at low Mach number (M<1.3) using both cylindrical as well as spherical density inhomogeneities. Using optical diagnostics, they very clearly visualized the transmitted, reflected, and refracted waves occurring in the interaction as well as the subsequent deformation of the resulting flow. A difficulty with these experiments is the low Mach number of the flow and the short time evolution which is too early to see the development of key hydrodynamic instabilities that are instrumental in destroying the cloud. Klein et al. [1-2] performed similar studies on the Nova laser studying shock-sphere interactions, extending the experiments into the strong shock regime (M>10) which is of interest to the astrophysics and carried out to long time evolution (~ >4 cloud crushing times t_{cc}.) A principal conclusion of Klein et al. [1-2] is that at late times the 3D vortex ring instability plays a critical role in the break-up of dense inhomogeneity (cloud) and is instrumental in the mechanism for mixing of the interstellar cloud with the ISM. The primary diagnostic in these experiments was x-ray absorption radiography. In each of these studies, the interaction was viewed from the side (direction perpendicular to that of shock propagation). While a great deal of information can be obtained from this viewpoint, a quantitative understanding of the non-axisymmetric instability and breakup requires an additional diagnostic view. The present experiments augment these previous studies by **simultaneously** diagnosing the interaction from two orthogonal views, thereby enabling the full three-dimensional topology of the interaction to be understood. These experiments are discussed in detail in Robey et al. [8].

2. EXPERIMENTAL SETUP AND RESULTS

The experiments are conducted on the Omega Laser [9]. Figure 1 shows a schematic illustration of the experimental setup that is used. The strong shock conditions of interest are achieved by directing 10 beams with a nominal measured energy of 500 J / beam, a flat temporal pulse of length 1 ns, and a laser wavelength of 0.351 μm onto the target. Each individual beam has a super-Gaussian spatial intensity profile defined as $I / I_0 = \exp[-(r / 412\mu m)]^{4.7}$. The combined spatial profile of all drive beams also follows this profile, with $I_0 = 9 \times 10^{14}$ W/cm^2. The intensity is reasonably constant over a central diameter of 600 μm, and falls off by about 10% by 800 μm. The target diameter, by comparison, is 800 μm. Since considerable laser energy extends laterally beyond the diameter of the target package, a 75 μm thick Beryllium shield with an outer diameter of 2.5-mm and an inner aperture of 950 μm was used to delay the propagation of a shock around the sides of the target. This proved to be successful in generating reasonably planar shock propagation through the target materials. Direct-drive laser illumination of the target was used in order to permit the face-on imaging of the interaction. Further details can be found in Robey et al. [8].

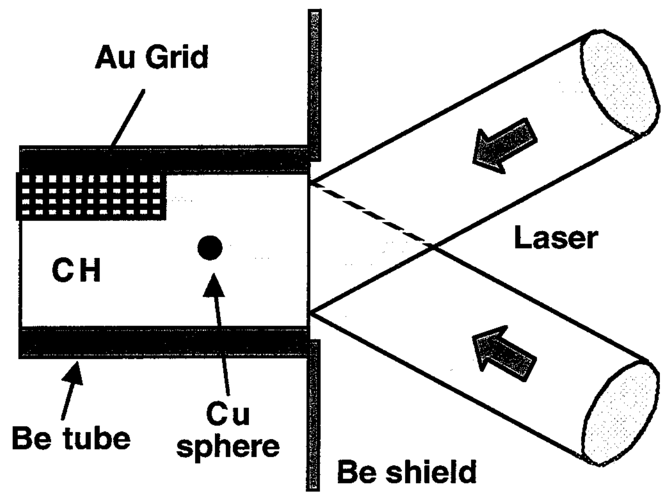

Fig. 1 Schematic of the experiment

Figure 2 shows experimental radiographs of the interaction in both the side-on and face-on directions at t = 13, 26, and 39 ns. In each case, the face-on images are delayed by 2 ns relative to the side-on images. Figures 2 (a & b) show images at t = 13 and 15 ns of the side-on and face-on structure, respectively. The shock is very clearly seen having just passed over the sphere. The shock is seen to be curved due to the non-uniform spatial profile of the initial laser energy deposition. The radius of curvature is much larger than the sphere diameter, however, so the interaction is reasonably approximated by a planar shock. The shock location is at 634 μm and the sphere is centered at 530 μm. The sphere is compressed in the longitudinal direction with a measured width of 80 μm. The lateral dimension of the sphere remains essentially unchanged at 120 μm. Figure 2(b) shows the corresponding face-on view of the sphere obtained 2 ns later. In this view, the sphere is seen to be essentially unperturbed, with a diameter that is essentially unchanged from its initial condition.

Figures 2(c & d) show the structure resulting at t = 26 ns. The shock, located now at 955 μm, has propagated ahead the sphere, which is now centered at 650 μm. The shock has become somewhat more planar, with an increased radius of curvature of 2 mm. The sphere is now considerably distorted in the direction of the shock propagation. In ref. [4], it was shown that baroclinic vorticity deposited by the shock on the surface of the sphere combined with Kelvin Helmholtz (K-H) instabilities and Mach reflected shocks produce the distortion. The corresponding face-on view of Fig. 2(d) shows that there remains a dense core of approximate diameter 70 μm in the center, with a 200 μm diameter surrounding region of lower optical depth. The reduced optical depth results primarily because this region has become a relatively thin hollowed out shell of Cu, as confirmed by the numerical simulations of [4-5].

Figures 2(e & f) show the continued distortion at t = 39 and 41 ns. The shock has now moved out of the field of view of the diagnostic. The vortical roll-up is very clearly seen in the side-on image of Figure 2(e), and the face-on view now shows a rather distinct double "ring" structure. The inner ring, which is the feature of greatest optical depth contrast in the image, exhibits a visible azimuthal mode structure with a mode number of 5. In the center of this ring is a region of reduced optical depth (or increased transparency). Surrounding the central ring is an outer ring that is seen to be significantly modulated in the azimuthal direction. Detailed 3-D calculations [5] indicate that these density ring structures are adjacent to baroclinically generated 3-D vortex rings at the cloud-ambient medium interface.

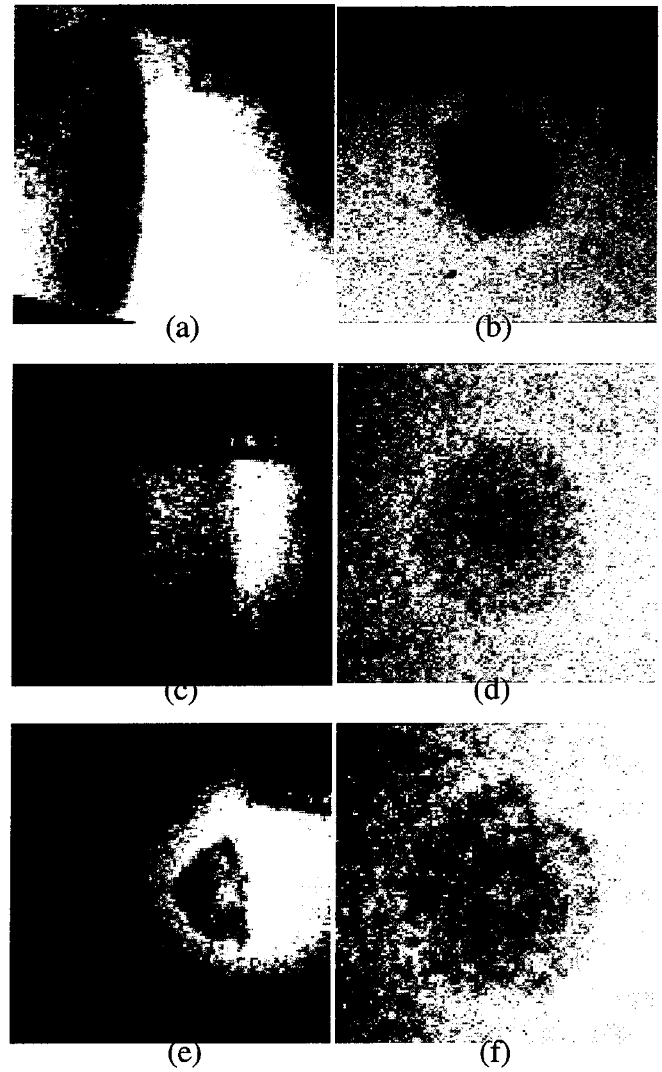

Fig. 2 Side-on (left side) and face-on (right side) radiographs of the shocked sphere at 13 ns (a & b), 26 ns (c & d), and 39 ns (e & f). Note that the scale on the face-on images is 2x that of the side-on images.

Figure 3(a) shows for comparison a second face-on radiograph from the experiment. This image was obtained on the same shot as the image of Figure 2(f), but at a slightly different time (Δt = 200 ps). These two images agree in the overall structure, but each exhibits differences in detail due to the temporally varying backlighter illumination pattern. In Figure 2(f), for example, the double ring structure was seen with a region of relatively reduced optical depth in the center. Figure 3(a), by comparison, does not reveal this inner ring structure as well, but rather brings out the dominant modal character of the azimuthal instability of the outer ring more clearly. The face-on structure can be analyzed quantitatively as follows. In Figure 3(b) we analyze the face-on structure by azimuthally-averaging the radial lineout obtained from Figure 3(a). Two hundred radial lineouts were taken over azimuthal angles $0 < \theta < 2\pi$ and averaged to form the radial lineout. To further increase the statistics, the procedure was repeated for 4 images separated in time by Δt = 60 ps. Figure 3(b) is the average over these four images, and quantifies the double ring structure. Beginning at r = 0, there is a region of approximately 30-40 μm in radial extent which exhibits a relatively high transparency (low optical depth). At r≈46 μm, the inner ring is seen with the lowest transparency. The second, outer ring is seen at r≈127 μm.

The azimuthal mode structure of the two rings is analyzed in Figures 3(c & d) by taking radially-averaged, azimuthal lineouts at r = 46 ±10 μm and 127±10 μm. These azimuthal lineouts were again averaged over 4 separate images. Figure 3(c) agrees with the visual observation of the images in revealing a dominant mode number of 5 for the inner and Figure 3(d) shows a higher mode number of 14-16 for the outer ring. This azimuthal modulation is seen in the image of Fig. 3(a) as well. The mode number spectra obtained by performing a Fourier transform of the averaged lineouts of Figures 3(c & d) are shown in Figures 3(e & f). We used the same procedure on a region of the face-on image outside of the distorted Cu sphere to obtain a spectrum of the background. For the inner ring, a peak is seen above the background level at a mode number of 5-8. For the outer ring two peaks are seen above the background level, one at a mode number of 5-6 and one at approximately 15.

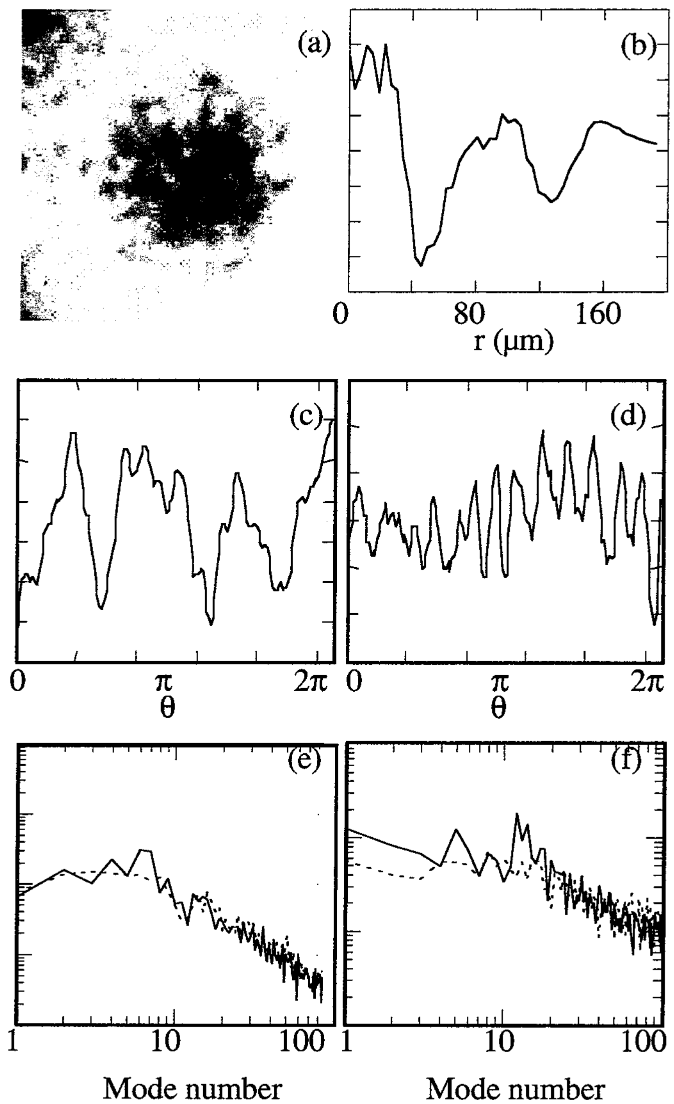

Fig. 3 (a) Face-on radiograph at 39 ns. (b) azimuthally-averaged, radial lineout through face-on image of (a). Radially-average, azimuthal lineout through (c) inner "ring" at r=50 μm and (d) outer "ring" at r =130 μm. Mode number spectra (e & f) corresponding to the azimuthal lineouts of (c &d).

Having now clearly identified the double ring structure in the face-on radiographs, one question remains. The side-on image of Figure 2(e) shows the outer vortex ring, but does not show the location of the inner ring. In order to fully complete the description of the three-dimensional structure, we must specify the axial location of this inner ring. Figure 4 shows a contour plot superposed on an enlarged image taken from Figure 2(e). One contour is shown at a gray-scale level that outlines most of the distorted Cu sphere. This contour very clearly shows the outer ring at the right-hand side of the object. The second contour level at a higher gray-scale level (more opaque) is shown as well. This contour locates the region of highest optical depth in the side-on view. Since the inner ring was the feature of greatest optical depth in the face-on view, this contour then gives the axial location of the inner ring. Figures 2(f) or 3(a) together with Figure 4 provide a complete three-dimensional description of the dominant features of this flow. In the next section we compare the modal structure of the unstable vortex rings with theoretical predictions.

3 COMPARISON WITH ANALYTIC THEORY FOR INCOMPRESSIBLE VORTEX RING INSTABILITY

In the work of Widnall, Bliss and Tsai [3], a theory was developed for short wave disturbances around the azimuth of a slender vortex ring in which the ratio of the vortex core radius to the ring radius is small. Using this theory and combining it with measurements from our radiographs of the rings, we can determine the non-dimensional translational velocity of the rings thus determine the dominant unstable ring mode. We find unstable modes of n=15-17 and n=5-7 for the outer and inner vortex rings respectively. These compare remarkably well with the unstable mode number we obtain from the experimental radiographs (n = 15 and n = 5 respectively). That the incompressible theory can provide a reasonable estimate of the unstable mode of the vortex ring structure inferred by detailed radiography of the highly compressible shocked sphere is quite remarkable. It can best be explained by realizing that at the time the vortex ring undergoes bending mode instability, all shocks have left the sphere, and it has passed through its compression and expansion phase and acts essentially as an incompressible fluid. A more detailed discussion of our work can be found in Robey et al. [8].

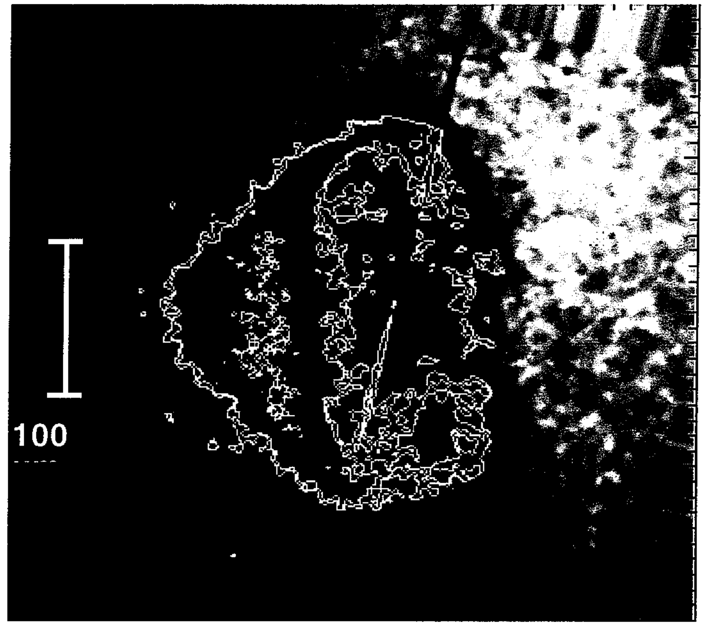

Fig. 4 Superposition of the side-on radiograph at 39 ns with contours outlining the distorted sphere and the location of the inner vortex ring.

4. CONCLUSIONS

The unstable breakup of the vortex ring that we have now observed for the first time, enhances the destructive effect of the K-H instability and this results in turbulence and breakup of the shocked sphere in direct analogy with the breakup of the shocked interstellar clouds [1,2,5]. The turbulent interstellar cloud leads to mixing with the ISM. Also, this unstable vortex ring mechanism may hold promise for explaining how turbulence may be generated in Giant Molecular Clouds that are externally shocked by multiple surrounding supernovae.

5. ACKNOWLEDGEMENTS

This work performed under the auspices of the U.S. Department of Energy by the University of California, Lawrence Livermore National Laboratory under contract No. W-7405-Eng-48.

6. REFERENCES

[1] R.I. Klein, K.S. Budil, T.S. Perry, D.R. Bach, *Ap.J. Suppl. Series* **127**, 379(2000).
[2] R.I. Klein, K.S. Budil, T.S. Perry, D.R. Bach, *Ap.J.* (2001) in preparation.
[3] S.E. Widnall, D.B. Bliss, C. Tsai, *J. Fluid Mech* **66**(1), 35 (1974).
[4] R.I. Klein, C.F. McKee, and P. Colella, *Ap.J. 420*, 213(1994).
[5] R.I. Klein, C.F. McKee, *Numerical Simulations in Astrophysics, Ed. Cambridge Univ. Press,* 251(1994).
[6] S.E. Widnall and J.P. Sullivan, *Proc. R. Soc. London* **A.332**, 335 (1973).
[7] J.-F. Haas and B. Sturtevant, *JFM* **181**, 41 (1987).
[8] H.F. Robey, T.S. Perry, R.I. Klein, J.O. Kane, J.A. Greenough, T.R. Boehly, *Phys. Rev. Lett.,* (2001) in press.
[9] J.M. Soures, R.L. McCrory, C.P. Verdon, *et al., Phys. Plasmas* **3**, 2108 (1996).

University of California
Lawrence Livermore National Laboratory
Technical Information Department
Livermore, CA 94551